Transaction Paper

A quality classification of building stones from *P*-wave velocity and its application to stone cutting with gang saws

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Synopsis

P-wave velocity measurements were carried out on 22 large limestone blocks in a stone processing plant. In the laboratory, *P*-wave velocity of core samples was measured to obtain intact rock velocity. The square root of the ratio of the velocity of the large stone block to the velocity of the core specimen was called the velocity ratio index (VRI) and a quality classification for large building stones was suggested. In addition, the applicability of the established classification to stone cutting with gang saws was checked. It was concluded that the quality classification and estimation of slab production efficiency of the building stones can easily be made by ultrasonic measurements. However, the study was carried out only in limestone. Further study must be conducted to check the validity of the obtained results for the other rock types.

Introduction

Ultrasonic techniques are increasingly being used in in various fields such as mining, geotechnical, civil, and underground engineering, since they are non-destructive and easy to apply. These techniques are usually employed both in site and laboratory to characterize and determine the dynamic properties of rocks. Attempts have been made to assess grouting (Knill, 1970; Turk and Dearman, 1987), rockbolt reinforcement (Price *et al.*, 1970) and blasting efficiencies in the rock mass (Young *et al.*, 1985) by seismic velocity determination. The prediction of rock mass deformation and stress (Onodera, 1963; Gladwin, 1982), the determination of rock weathering degree (Karpuz and Pasamehmetoglu, 1997), rock mass characterization (Boadu, 1997; Turk and Dearman, 1986) and the estimation of the extent of fracture zones developed around underground openings (Hudson *et al.*, 1980) are some other applications of the seismic techniques. Most researchers (D'Andrea *et al.*, 1965; Deere and Miller, 1966; Youash, 1970; Saito *et al.*, 1974; Gardner *et al.*, 1974; Lama and Vutukuri, 1978; Inoue and Ohomi, 1981; Gaviglio, 1989; Yasar and Erdogan, 2004) studied the relations between rock properties and sound velocity and found that sound velocity is closely related to rock properties.

There are a number of factors that influence the sound velocity of rocks. The important factors are rock type, density, elastic properties, grain size and shape, porosity, anisotropy, porewater, confining pressure and temperature. Weathering and alteration zones, bedding planes and joint properties (roughness, filling material, water, dip and strike, etc.) have also an important influence on the sound velocity.

Many different rocks are used as building stone in the construction industry. The fractures in a large stone block are the principle factor that determines its quality. The slab production efficiency of a stone block depends on the fractures in it. The quality determination of the building stones is very important for saving and planning of the stone processing plants. Generally, the quality determination of the building stones is still made by visual inspection and the risk of error is high. Outer fractures can be seen while the depth of outer fractures and the presence of inner fractures cannot be estimated by visual inspection alone. In this study, a quality classification of large building stones from *P*-wave velocity measurements was suggested and its application to the stone cutting with gang saws was presented.

Field studies

The study was performed on a limestone

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Table I

Average physico-mechanical properties of the tested rock

Density (g/cm³)	Porosity (%)	Compressive strength (MPa)	Tensile strength (MPa)	P-wave velocity (km/s)
2.66	0.66	100.9	7.8	6.3

(Amasya Classical Beige) from Amasya (Turkey). The rock is of Jura-Cretaceous age and generally has no bedding. In a stone processing plant, *P*-wave velocity measurements were carried out on 22 large limestone blocks. The large limestone blocks had smooth surfaces since they had already been cut by diamond wire at the quarry. Each parallel side of the block was systematically marked with paint, as shown in Figure 1. The distance between each measuring point and between each row was 25 cm. Using a PUNDIT 6 instrument with exponential (conical) transducers, measurements were conducted. *P*-wave velocity values were calculated using the following formula:

$$V_p = \frac{d}{t_p} \qquad [1]$$

where V_p is the *P*-wave velocity (km/s), d is the distance between transmitter and receiver, and t_p is the time that the *P*-wave takes to travel the distance d.

After the calculation of the *P*-wave velocity at each measuring point, the average value was recorded as the velocity of the block.

Laboratory studies

To determine the physico-mechanical properties of the sawed rock, small block samples were collected from the site for the laboratory tests. Core samples were prepared from blocks and density, porosity, uniaxial compressive strength, tensile strength and *P*-wave velocity were carried out according to the standard methods (ISRM, 1981).

Density test

Trimmed core samples were used in the determination of dry density. The specimen volume was calculated from an average of several calliper readings. The dry weight of the specimen was determined by a balance, capable of weighing to an accuracy of 0.01 of the sample weight. The density values were obtained from the ratio of the specimen weight to the specimen volume.

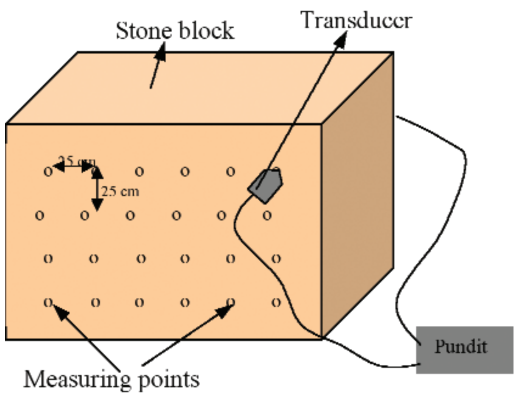

Figure 1—*P*-wave velocity measurements on large stone blocks

Porosity test

Porosity values were determined using saturation and calliper techniques. Pore volumes were calculated from dry and saturated weights and sample volumes were obtained from calliper readings. The porosity values were obtained from the ratio of the pore volumes to the specimen volume.

Uniaxial compressive strength test

Uniaxial compression tests were performed on trimmed core samples, which had a diameter of 38 mm and a length-to-diameter ratio of 2. The stress rate was applied within the limits of 0.5–1.0 MPa/s.

Brazilian tensile strength test

Brazilian tensile strength tests were conducted on core samples having a diameter of 38 mm and a height to diameter ratio of 1. The tensile load on the specimen was applied continuously at a constant stress rate such that failure would occur within 5 min of loading.

Ultrasonic test

The *P*-wave velocity of intact rock was measured on core samples using the PUNDIT 6 instrument. Core samples had a diameter of 47.3 mm and a length of 94.5 mm. End surfaces of the samples were polished to a sufficiently smooth plane to provide good coupling. A good acoustic coupling between the transducer face and the rock surface is necessary for the accuracy of transit time measurement. Stiffer grease was used as a coupling agent in this study. Transducers were pressed to either end of the sample and the pulse transit time was recorded. *P*-wave velocity values were calculated using Equation [1].

The measurements were performed three times on the samples collected from the different locations of the quarry and average value was recorded as the *P*-wave velocity value.

Average values of density, porosity, uniaxial compressive strength, tensile strength and *P*-wave velocity are given in Table I.

Classification method

An index called a velocity ratio index (VRI) was defined from ultrasonic measurements on the stone block and intact rock specimen. VRI formulation is given below:

$$VRI = \sqrt{\frac{V_B}{V_L}} \qquad [2]$$

where VRI is the velocity ratio index, V_B is the velocity of the stone block, and V_L is the velocity of the core specimen.

VRI values range from 0 to 1. The block quality was divided into five categories according to VRI as shown in Table II.

VRI is defined as the square root of the ratio between V_B and V_L instead of only the ratio between V_B and V_L to obtain conformity between the VRI index and observed slab efficiency. Let us explain this by an example: For block number 1 (Table III) the ratio between V_B and V_L is 0.44. If this block is classified according to the value of 0.44, the block quality will be poor. However, the observed slab efficiency of this block is 85.5% and this efficiency is not poor in practice. On the other hand, the square root of 0.44 corresponds to 0.66. For a VRI value of 0.66, the block quality will be fair and this will conform to practical applications.

Application of the classification method

Using laboratory and block *P*-wave measurements, VRI values for each block were calculated from Equation [2]. Then, each block was classified according to Table II. VRI values and classification of each block are given in Table III. As shown in Table III, 4 blocks are very good quality, 4 blocks are good quality, 14 blocks are fair quality, and 1 block is poor quality.

Gang or frame saws are extensively used for economical manufacture of slabs from quarried large blocks of soft stone, marble, travertine, limestone, etc. in stone processing plants (Figure 2). Cutting the 22 large limestone blocks with a gang saw was observed and the number of sound and broken slabs was recorded. After that, the efficiency of slab production for each block was calculated from the following formula:

$$\eta_s = \frac{N_{is}}{N_{ts}} x100 \qquad [3]$$

Table II

Quality classification of stone blocks

VRI	Block quality
<0.25	Very poor
0.25–0.50	Poor
0.50–0.75	Fair
0.75–0.90	Good
VRI>0.90	Very good

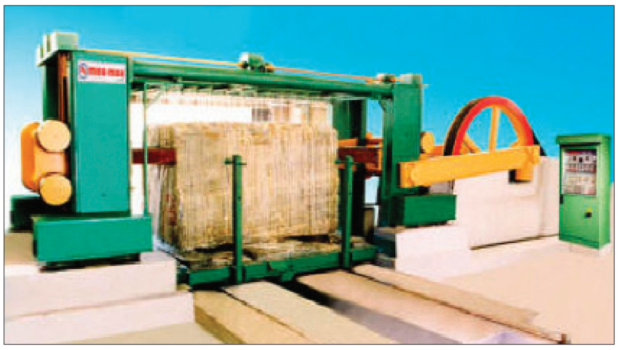

Figure 2—Gang saw during the cutting

where η_s is the slab efficiency (%), N_{is} is the number of intact slabs cut from block, and N_{ts} is the theoretical number of slabs that can be cut from the block.

Slab efficiency values of the 22 large limestone blocks are given in Table III. As shown in Table III, the slab efficiency values range form 76.5% to 100%.

To check the applicability of the classification method to stone cutting with a gang saw, VRI values of blocks and slab production efficiency values were evaluated using regression analysis and the correlation coefficient was determined. A strong correlation between VRI values and slab production efficiency values was found (Figure 3). The relation follows a logarithmic function and correlation coefficient (r) is 0.84. Slab efficiency increases with increasing VRI. The equation of the curve is

$$SE = 26.96 \ln(VRI) + 97.4 \qquad [4]$$

where *SE* is the slab efficiency (%) and VRI is the velocity ratio index.

To see the estimation capability of Equation [2], the graphs of observed slab efficiency versus predicted slab efficiency were plotted. As shown in the Figure 4, the points are scattered uniformly about the diagonal line, suggesting that the model is reasonable.

Conclusions

After laboratory and field studies, a quality classification of

Table III

Classification and slab efficiency of tested stone blocks

Block no	Velocity ratio index (VRI)	Block quality	Observed slab efficiency (%)
1	0.66	Fair	85.5
2	0.68	Fair	85.7
3	0.71	Fair	87.0
4	0.68	Fair	85.1
5	0.57	Fair	80.4
6	0.71	Fair	86.6
7	0.66	Fair	90.8
8	0.66	Fair	90.8
9	0.77	Good	95.9
10	0.75	Good	88.2
11	0.91	Very good	92.1
12	0.99	Very good	100.0
13	0.77	Good	94.1
14	0.69	Fair	83.8
15	0.99	Very good	93.5
16	0.57	Fair	87.8
17	0.69	Fair	85.7
18	0.49	Poor	76.5
19	0.68	Fair	86.8
20	0.95	Very good	97.4
21	0.68	Fair	82.7
22	0.70	Fair	89.1

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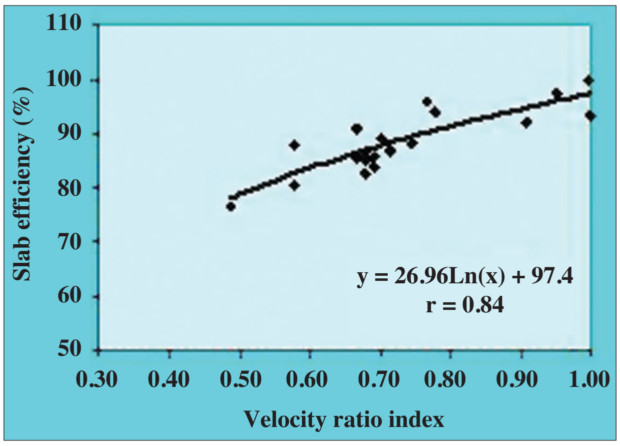

Figure 3—The correlation between velocity ratio index and slab efficiency

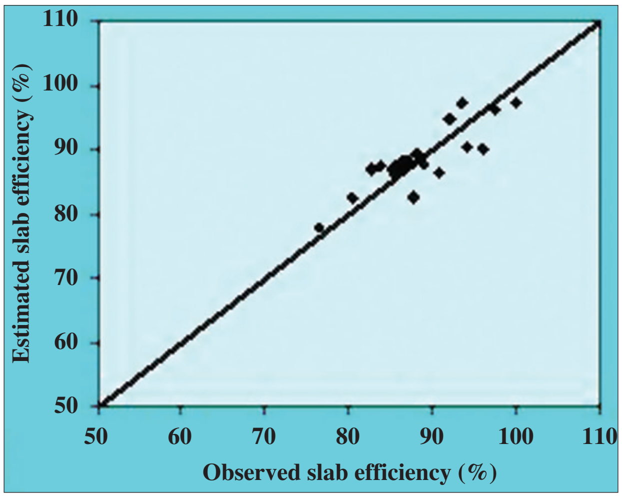

Figure 4—Estimated slab production versus observed slab production

large building stones from *P*-wave velocity measurements was established and its application to the stone cutting with gang saw was presented. A concluding remark is that the quality classification and estimation of slab production efficiency of the building stones can be made by ultrasonic measurements. The method is cheap and easy to apply. However, the validity of the obtained results for the other rock types must be checked further. In addition, investigating the possibility of improving the study by describing the orientations or positions of the cracks in the blocks may be another future study.

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